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Applying blockchain in the geoenergy domain: The road to interoperability and standards

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HIGHLIGHTS

- Blockchain can potentially improve sustainability and efficiency of geoenergy industry.
- Case study evidence presented showing what geoenergy industry can learn from other sectors.
- Absence of data standards and interoperability diagnosed as barriers to getting value from blockchain.
- Geoenergy sector should leverage existing data standards as much as possible from other industries.

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ABSTRACT

Geoenergy sources will continue to be mainstays of the world's energy mix for many years to come, but the technological and business realities behind these energy sources are changing in two fundamental ways. First, with much of the world's "easy oil" already consumed, the companies behind geoenergy will have to use increasingly sophisticated technologies to find and deliver these energy sources to the market. Second, the expectations placed upon the geoenergy sector by many of its stakeholders have grown considerably with regards to environmental stewardship, safety, and human welfare. In the face of these kinds of challenges, the industry will require an increasing degree of technological and commercial sophistication to continue to be a part of the world's sustainable energy mix. Blockchain has emerged as a promising innovation that could potentially play an important role in delivering the kinds of technological and commercial capabilities that the geoenergy sector will need to achieve these ends. In spite of the myriad ways that blockchain could potentially improve the efficiency and sustainability of the geoenergy industry, however, the technology is still evolving, and a few barriers stand in the way of its widespread deployment. This paper puts forward case study evidence from the Intel Corporation and the Energistics Consortium showing what the geoenergy sector can learn about blockchain from other industries, and highlights that the absence of data standards and interoperability has contributed to blockchain's failure to deliver significant value in the geoenergy domain thus far.

1. Introduction

Geoenergy sources—defined here as naturally occurring energy resources found within the earth's crust, including oil & gas, oil sands, coalbed methane, and geothermal energy—have been an important part of the world's energy mix for decades [1], and this trend is expected to endure for many years to come [2–8]. While the global demand for these energy sources continues, however, the technological and business realities behind them are changing in two fundamental ways. First, with much of the world's "easy oil" already consumed [9,10], the companies behind geoenergy will have to use increasingly sophisticated technologies to find and deliver them to the market [11–13]. Future geoenergy resources—especially in non-OPEC countries—will tend to be deeper, harder to find, and in environments that are significantly more difficult to access than they used to be [14–16].

Second, high-profile disasters like the *Piper Alpha* incident in 1988 [17], the *Exxon Valdez* oil spill in 1989 [18,19], Shell's *Brent Spar* incident in 1995 [20–22], and the *Deepwater Horizon* accident in 2010 [23,24] have brought about a marked change in the expectations placed upon the geoenergy sector with regards to environmental stewardship,

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safety, and human welfare [25–27]. In the face of these kinds of challenges, the industry will require an increasing degree of technological and commercial sophistication to continue to be a part of the world's sustainable energy mix [6,28].

Blockchain has emerged as a promising innovation that could potentially play an important role in delivering the kinds of technological and commercial capabilities that the geoenergy sector will need to achieve these ends. Blockchain is essentially "a mathematical structure for storing data in a way that is nearly impossible to fake" [29], which makes it a useful way to reliably share a broad range of valuable information [30–32]. In the finance sector, blockchain is most famously known as the technology underlying cryptocurrencies like Bitcoin, but new applications are being discovered all the time—including in the geoenergy domain. Companies in the industry have already made inroads into the blockchain domain by using the technology to improve trading [33], guarantee the authenticity of wellbore rock and fluid samples [34], and create a shared consensus about the progress of drilling campaigns [35]. In fact, there is so much attention focused these days on the application of blockchain in the geoenergy area that several consortia and research initiatives have popped up to figure out new and inventive ways to deliver value with these kinds of innovation.

In spite of the myriad ways that blockchain could potentially improve the efficiency and sustainability of the geoenergy industry, however, the technology is still evolving, and a few barriers stand in the way of its widespread deployment. Figuring prominently among these is the lack of standardization and interoperability among technology platforms within the blockchain technology space [36]. Towards addressing this gap both in the academic literature and the practitioner domain, this paper will begin by offering a brief distillation of the literature about the state of the art in blockchain technologies and how they have shown promise for delivering value in a range of industries, including in the geoenergy sector and in elsewhere in the marketplace. This literature will show, however, that the energy industry has for the most part failed to derive large-scale value or benefit from blockchain so far—an outcome that has been blamed at least in part on the absence of standards and interoperability [36]. We then try to shed new light on this part of the problem by examining relevant literature in the area of digital standards and interoperability, and by specifically discussing the geoenergy industry's previous experiences with these kinds of technological challenges. This intersection of prior research in the blockchain domain and literature about data standards and interoperability in the context of geoenergy will then be synthesized into the research questions put forward in this paper. Specifically, these questions will consider how other industries are applying blockchain technologies, what the geoenergy sector can learn from these applications, and whether the industry should actively move towards industry-wide data standards and greater interoperability.

Therein lies the main objective of this paper: to answer these questions by presenting case study evidence from the Intel Corporation and several geoenergy industry experts who explain at a conceptual level how blockchain technology is being experimented with in the energy domain, and how the geoenergy sector has managed its way through previous experiences with data standards and interoperability. In doing so, this paper contributes to this area by exploring potential pathways for delivering value and improving the sustainability of the geoenergy sector with this innovation. We will then conclude with recommendations about how the geoenergy industry could potentially do more with blockchain to improve its overall efficiency and sustainability, explicitly identify the theoretical and practical contributions that this paper makes, and offer some suggestions for future investigations in this area.

2. Literature review and research questions

2.1. What blockchains are and how they deliver value

Blockchain is essentially a mathematical structure for storing data in a way that is nearly impossible to fake [29,30]. Bitcoin and digital currencies are the most famous and conspicuous examples of this innovation but, beyond digital money, the technology has also been applied within supply networks to transparently share data that can be trusted even if the participating organizations do not entirely trust one another [37]. On a technical level, blockchains consist of:

> … a ledger that may contain digital transactions, data records and executables. Transactions are aggregated into larger formations, called *blocks*, which are time-stamped and cryptographically linked to previous blocks forming a chain of records that determines the sequencing order of events or the "blockchain." Apart from describing the data structure itself, the terminology is also broadly used in the literature to represent digital consensus architectures, algorithms, or domains of applications built on top of such architectures [36,p. 145].

The primary purpose of blockchain technologies is to remove the need for any kind of centralized management of digital records and replace it with a distributed network of digital users who collectively work to verify transactions and, in doing so, safeguard the integrity of the ledger [29,36,38]. As shown in Fig. 1, users can agree on a transaction that is a part of a block, and its validity is confirmed by distributed nodes of the network. The block is then added to the growing chain of blocks before each transaction is confirmed.

Simply put, blockchain technology is all about creating faith in the veracity of a system [37]. "There are different kinds of consensus protocols… [but] the common thread between all of them is that mathematical rules and impregnable cryptography, rather than trust in fallible humans or institutions, are what guarantee the integrity of the ledger" [37,p. 13].

The benefits of trust in commercial transactions and inter-organizational exchanges are largely achieved by improving the predictability and reliability of collaborators, thereby helping to reduce the transaction costs associated with these activities [39–45]. But as the geoenergy industry becomes increasingly digital in nature [46,47], trust will also be an important foundation for several of the innovations that are finding their way into the sector. For example, "the internet of things,

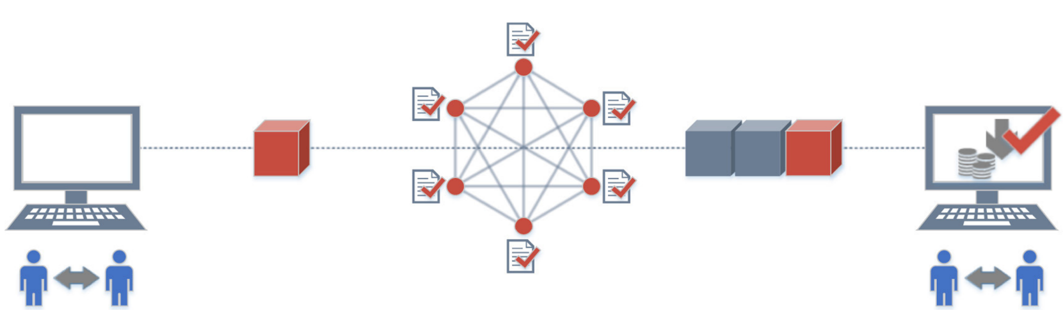

Fig. 1. Visual Representation of a Blockchain Transaction [36].

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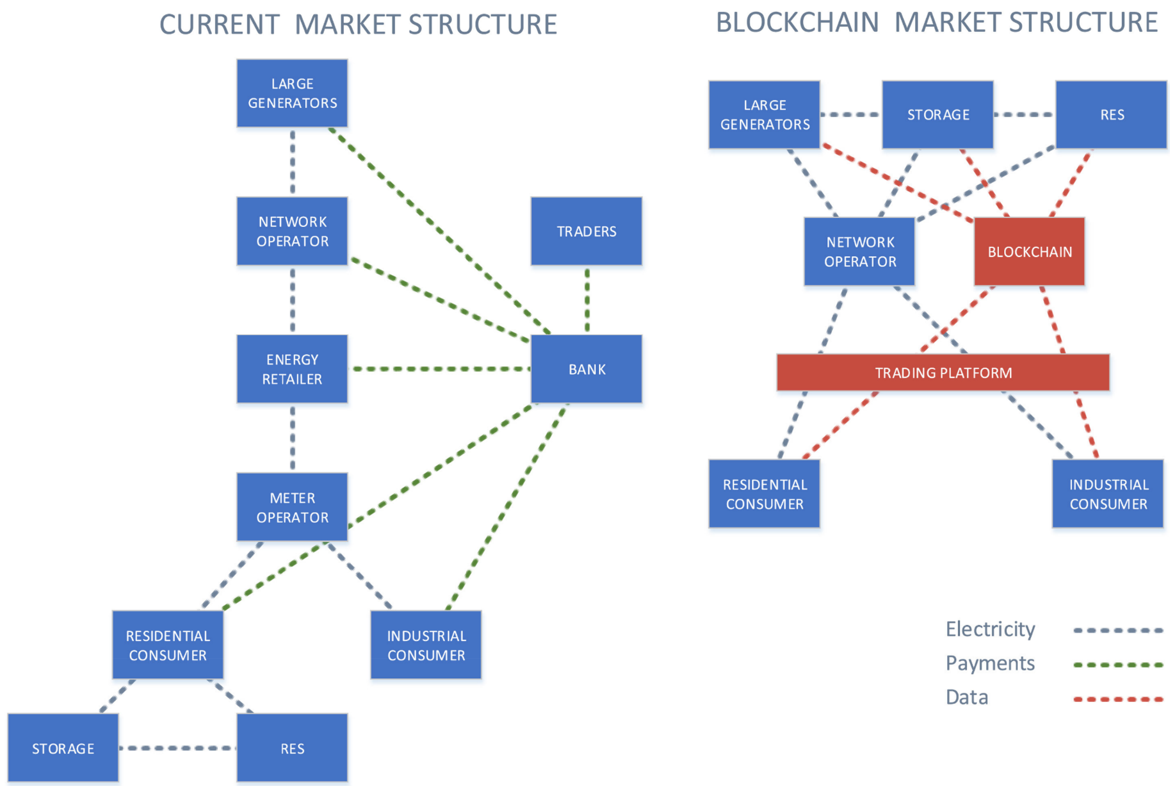

Fig. 2. Potential Transformation of Electricity Market with Blockchain [36].

which it's hoped will have billions of interacting autonomous devices forging new efficiencies, won't be possible if gadget-to-gadget micro-transactions require the prohibitively expensive intermediation of centrally controlled ledgers" [37,p. 14]. In this way, blockchain has the potential to act as an enabling technology en route to helping the geoenergy sector take full advantage of the internet of things and other new innovations like it.

2.2. Blockchains in use in other industries

Early experiments with blockchain have delivered promising results in a broad range of market contexts beyond the finance and banking industry [e.g.,48,49]. For example, the technology has been used in the electricity sector to facilitate machine-to-machine interactions so that producers and consumers can trade with one another, effectively creating a small-scale market [50]. As Andoni et al. [36] point out, "the potential of blockchain for wholesale energy trading has been highlighted in a number of sources, with some consultancy reports [51] even arguing that it has the potential to transform the current energy market structure" (p. 152) as shown in Fig. 2. Blockchain has also been suggested as a way for delivering "smart cities" that bring together new kinds of information technologies to support communal sharing and greater efficiency [52], and for actively managing carbon emissions [53]. The increase in system-wide transparency made possible by blockchain technologies also has tremendous potential in industries like pharmaceuticals that need to have tight end-to-end control of complex manufacturing processes throughout their value network [54], or sectors like the diamond industry that are eager to quash markets for illegal or counterfeit products [55].

The healthcare sector has also been particularly aggressive about promoting the use of this innovation in that industry [e.g.,56,57]. Because health-related data is often shared among multiple sources such as doctors, clinics, insurance companies, and government agencies, the ownership and truthfulness of this information is extremely important. The appeal of blockchain in this kind of context is rooted in the fact that it can help to reduce—and, in the best cases, even eliminate—errors in patient records and test results while also improving the security of these data transactions [58].

2.3. How blockchain has been used in the geoenergy sector

Blockchain has been used to manage market transactions in the geothermal energy [59,60], electricity [61], renewable energy [62], and oil & gas [33,63] industries, but less attention has been paid to the technical dimensions of the geoenergy space. The oil & gas sector has made some early forays into applying this innovation to more technical challenges—like, for example, using it to guarantee the authenticity of wellbore rock and fluid samples [34] or creating a shared consensus about the progress of drilling campaigns [35]—and several consortia and research initiatives have emerged in the industry to explore new and inventive ways to deliver value with blockchain in the oil & gas market, including the Enterprise Ethereum Alliance[1] (for which the Intel Corporation was a founding member) and the Oil & Gas Blockchain Consortium[2]. But for the most part, these more technically inclined attempts at using blockchain in the geoenergy industry are in varying degrees of experimentation rather than being mature, broadly deployed technologies [64]. What is more, they are frequently variations on the same basic model of value delivery that underpins many blockchain applications elsewhere in the marketplace.

The comparatively small number of contributions in the blockchain literature from the geoenergy industry and the relatively nascent stage of the technology's practical applications suggest that, in many ways, several other industries—in particular, the healthcare and finance

[1] https://entethalliance.org/. The Alliance states that its mission is to be "a member-driven standards organization whose charter is to develop open blockchain specifications that drive harmonization and interoperability for businesses and consumers worldwide."

[2] https://www.oocblockchain.com/

sectors—have moved further and faster in this technology area than the geoenergy sector has. But the geoenergy industry has been characterized over many years as being relatively slow to adopt new technologies in general [e.g.,8,46,65,66–70], and this slower rate of uptake for blockchain-related innovations is consistent with that larger trend. The other side of this coin, however, is that the geoenergy industry could potentially benefit from the valuable learning and experimentation that has already occurred in other industries' respective journeys to blockchain. This leads to:

Research Question 1a: How are other industries applying blockchain technologies in ways that are different from what is happening in the geoenergy sector?

Research Question 1b: What can the geoenergy industry learn from other sectors with regards to using blockchain technologies?

The kind of fluid, experimental phase that blockchain is in within the geoenergy domain happens in the early days of many new innovations [71,72], and this is in many ways a healthy process inasmuch as it means that a lot of new ideas are being explored, which often results in a more robust dominant design [71]. It also means, though, that there are many varieties and architectures of blockchains available in the market from a broad range of vendors. An obvious challenge arising from this is that it results in scenarios where incompatible system architectures can prevent would-be collaborators from working together or integrating their systems [36]. But as discussed in the next section, the geoenergy industry has faced the challenge of data standards and interoperability before, and a look back at this period in the industry's history may therefore shed a useful amount of light on the current situation with blockchain.

2.4. The emerging need for data standards and interoperability

The issue of interoperability has already emerged in other industries' journeys to applying blockchain. The healthcare sector in particular has wrestled extensively with these challenges [73–75], but these issues have also emerged in a range of other contexts ranging from government [76] to agriculture [77]. While the geoenergy industry has not done much to specifically address these challenges in the context of blockchain, it has dealt with similar problems when digital technologies were first making their way into the equipment provided by oil & gas service companies.

Like many industries at the time, the upstream oil & gas sector became increasingly reliant on electronic instrumentation and digital information in the 1970s and 1980s [78]. Early attempts to share digital information between different parts of the industry were met with frustration because of the myriad data transfer standards that had emerged throughout the sector. Towards solving this problem, a handful of operators—BP, Chevron, Elf, Mobil, and Texaco—came together to develop the Petrotechnical Open Software Corporation (POSC) in 1990 [79,80]. POSC was essentially a consortium established to develop, support, and promote open data standards for the upstream oil & gas sector. The POSC community has broadened considerably over the years to include many new members around the globe, and the organization re-branded itself as Energistics in 2006. The steady growth in the size of the Energistics community and the number of organizations applying their standards are evidence of the fact that several stakeholders within the industry believe that the presence of these standards has delivered value to the sector. The literature has already pointed to the absence of standards and interoperability as a significant barrier for the uptake of blockchain within the energy industry overall [36], and this logic extends to the geoenergy domain as well. Thus:

Research Question 2: How should the geoenergy industry move towards industry-wide data standards and interoperability that will allow blockchain to deliver more value?

3. Methodology

A qualitative case study methodology was used to capture a more complete, holistic, and contextual understanding of how blockchain is being used in other industries and the geoenergy domain [81]. Following Yin [82], we used a case study method because this is a preferred strategy when "how" or "why" questions are being posed, and when the focus is on a contemporary phenomenon. Qualitative research methodologies have been used relatively sparingly in the energy literature[3] [e.g.,85,86,87], but case studies can help to establish the internal validity of findings because "[w]hen a relationship is supported, the qualitative data often provide a good understanding of the dynamics underlying the relationship" [88,p. 542] and can make clear when an apparent relationship is spurious or the result of an additional variable not originally considered in the research design.

The data for this case study was collected via a series of semi-structured interviews involving senior-level managers and technical experts from the Intel Corporation and from Energistics Consortium senior-level managers and community members during the period 2018–2019. The names of specific participants have been withheld as a way of encouraging honesty and candid perspectives. Because Intel creates semiconductor chips and related technologies that are broadly available throughout the entire marketplace, the company and its employees are well situated to observe technology trends unfolding in different market segments. It therefore follows that the company's managers are a valuable resource for understanding how innovations like blockchain are being absorbed and experimented with differently from one sector to the next. Participants from Intel were selected to capture the experiences and learning points that had come into focus throughout the implementation of blockchain technologies both within the energy sector and further afield in the marketplace. When Research Question 2 was added to the research agenda because of the emerging importance of data standards and interoperability in the earlier rounds of interviews, additional interviews were added with members of the Energistics Consortium.

The interviews were conducted both in person and via telephone with a total of 17 individuals, from which over 14 h of dialogue was digitally recorded and transcribed. Each of the discussions lasted between 30 and 70 min and was loosely guided by a list of questions (Appendix A), but departures from each conversation's agenda were permitted in the interest of exploring new and potentially fruitful points. The format of the discussions was accordingly adapted and changed slightly from one discussion to the next to pursue interesting and particularly relevant new facets of the case study as they emerged.

Yin [82] and Flick [89] both recommend using multiple sources of evidence in case studies to "triangulate" among various points of view and minimize the amount of subjectivity within the study. To this end, multiple participants were asked essentially the same question to determine if and to what degree their responses were in agreement. This approach was used to arrive at conclusions that are as broadly in agreement and reproducible as possible. Then, following Yin [90], particularly relevant quotations were extracted from the interviews and highlighted in the next section in a way that directly addresses the research questions identified in Section 2. Observations and conclusions were then documented and shared with the participating managers to

[3] It is worth noting, however, that case study and qualitative types of research are arguably becoming more common in the energy literature. In a high-profile *Nature* paper, Sovacool [76] calls for more social science research in the energy domain. Also, the journal *Energy Research & Social Science* was launched as recently as 2014, but has quickly become a respected and impactful journal in the energy discipline. Qualitative research methods are a frequently recurring feature in the social sciences [77], and it is therefore reasonable to expect that these methodological approaches will probably become more common in energy research as this field continues to establish more and deeper connections with the social sciences [83,84].

make sure that the case study accurately and fairly reflected their opinions.

4. Case study

Several interesting themes emerged from the interviews that are highly relevant to the geoenergy domain and the larger market around it. One point of agreement among several participants was that there is a significant amount of unevenness in the usefulness of blockchain throughout the marketplace. The Intel interviewees did agree that the financial, transportation, healthcare, and logistics sectors have made significant progress with finding genuinely useful applications for blockchain, but noted that many other industries had been struggling to achieve these kinds of gains—including the geoenergy sector. "There's been too much hype around this," said one senior manager from Intel. One of their colleagues added that:

> If you look at the IT industry, most of them really have no idea what the [geoenergy] business is about. There are only a few companies selling blockchain to the energy industry that really understand the processes and the business. So, yeah, as a result, there's a lot of mis-selling going on.

An interviewee from Energistics enthusiastically agreed with this sentiment, and added:

> In many ways, blockchain is a solution looking for a problem to fix. And this industry is a target-rich environment. I could see blockchain potentially adding value in several focused areas like managing contracts and safety processes. But just because we can use this technology doesn't mean that we always necessarily should. There are other parts of the industry like geophysical or subsurface data, seismic data, or production data where blockchain might not add much value.

An Intel engineer pointed out that there are also some fairly fundamental technical issues getting in the way of blockchain delivering value to the geoenergy sector. Of particular importance among these is the fact that the technology is still relatively nascent and undeveloped:

> From a technology perspective, the technology is still relatively immature. Bitcoin was invented like, what, eight or nine years ago? But nobody on the enterprise side was really looking at this technology probably until about three years ago. And many of the blockchain solutions aimed at the enterprise market only hit their "1.0" releases within the past year. So the software hasn't really been mature enough to take into a production environment until the past 12 months. And some of the technology that is coming out as "1.0" isn't really ready to go yet.

But several of the engineers and managers from Intel did see some patterns in the success stories from several sectors that could help the geoenergy industry figure out how to make blockchain yield better results in the future. In the words of one participant:

> Any time you have a change of custody of something, you have an opportunity for blockchain. It's a lot harder to apply this idea to continuous flow systems. You'll never really get down to the situation where you have a box of oil, and that makes it difficult to apply blockchain in many parts of the upstream oil & gas industry. But when you get to the refinery, now you have a situation where products are coming out. Now you can start to apply blockchain to that product. But until that point, you really have a continuously flowing stream where it's harder to use blockchain.

One of the Intel engineers offered additional explanation on this particular problem and, in doing so, they also explained why blockchain has taken root first and most successfully in mostly digital market spaces like finance while making less progress and delivering less utility in businesses more directly connected to the physical world:

> The blockchain can only guarantee the integrity of the digital asset. It can't protect the integrity of the physical asset. There's always these issues when you try to build that kind of physical-digital bridge. There's always room for mischievous behavior at that interface.

As so often happens in these situations, however, the technology is not the only potential barrier that the geoenergy industry faces en route to delivering value with blockchain. A senior manager from Intel pointed out that his earlier attempts at embedding the technology in other industries had resulted in some important learnings about the organizational and human dimensions of the problem that would-be users of blockchain within the geoenergy domain would do well to learn from:

> The biggest barriers to blockchain are less about the technology and more about the people. The projects that seem to make it are the ones where all of the people involved have a seat at the table before the project starts. Most other companies don't want to sign up to a development program that's already underway and being led by some other big company. It's really hard to bring people into your network if they didn't have a say in the beginning.

Despite the technical and people-related challenges associated with implementing blockchain, however, some parts of the geoenergy value network have gone much further than others and made considerable progress. Specifically, the Intel team saw significant potential for blockchain technology in the downstream oil & gas industry, and revealed that many noteworthy successes had already been achieved there. One manager reported that:

> A lot of these innovations are driven by oil & gas… by the downstream guys. They've done a good job of developing standards. By that, I mean you agree on the exchanges between the black boxes that you are going to put in. And all the black boxes can talk to the other black boxes… This is being driven by downstream oil & gas, and these developments are going to have an impact on how blockchain happens in other markets. And then these standards are going to be pushed into the market by other IT companies.

And just as the literature revealed the changing nature of inter-organizational trust between firms using blockchain [37], the interviews confirmed this—but one engineer went further by pointing out that this new reality has opened up some interesting possibilities within the marketplace:

> Companies will be able to demonstrate 100% compliance with the click of a button… So the question becomes "How can we show validity and compliance from mom & pop firms?" The big companies that have always had a great reputation in the industry… they'll be able to show that they are compliant. But with blockchain, so can the small firms.

In other words, the participants explained that trust and reputation will be far less important in value networks governed by blockchain than has historically been the case. Whereas some companies have been the beneficiaries of repeat customers for many years because of the development of long-term relationships between firms, those linkages could conceivably mean much less in this new business environment because a prospective customer firm can instantly access the long-term performance record of every company that they might be considering to provide a component or service. "Blockchain creates trust between previously unknown participants in a market. At its heart, that's what it does," explained one of the Intel managers. To explain this point, the participant put forward as an example Walmart's blockchain-based system for managing perishable food items [91]. "Does this make the customer more likely to trust the safety of that food? Of course it does."

But it was also revealed in the interviews that the drive for system-wide transparency underpinning blockchain carries with it some potentially unhelpful downsides, too. One Intel participant emphasized that:

> The thing that makes some people reticent to use blockchain is that all transactions are visible. If somebody is mining the data in the chain, they can see all the transactions that are happening. Your competitors can also see exactly what activities you have been up to in your operations. They can see that you've had a lot of transactions over here or over there. For example, if I see that a company has suddenly tripled the amount of trucking activity in a certain area, then I can see that there's been a surge in the amount of activity happening in that area for my competitor. So what needs to happen for these people to use the technology is that they need to be able to obfuscate some aspects of their transactions so that they are not revealing too much information to competitors about the specifics of their operations.

It emerged during the interviews that data standards and interoperability were also important topics in this area that warranted further exploration, and several participants were accordingly asked for their perspectives and ideas on this. When pushed for direct comparisons between the case for digital standards in blockchain and the development of POSC (the precursor to Energistics) in 1990, an Energistics executive explained that the two situations are different in some important ways:

> Those are very different scenarios. When the industry was bringing things together with POSC, the vendors providing us with the digital technologies were oil & gas service companies. That's not what's happening with blockchain. Instead, this time the vendors are not from the energy industry—like, for example, IBM. And they've already done this stuff in other sectors. That wasn't really the case with the digital technologies that gave rise to POSC.

And whereas the geoenergy industry essentially had to develop its own data standards and work internally to bring about interoperability within the sector's digital technologies, the prevailing thinking among interviewees is that the blockchain situation is materially different. An Energistics executive observed that:

> While there are certain things that are unique to the energy industry… we would be incredibly naïve and arrogant to create a standard that suits just energy without considering what has been done in other sectors to see if they have already tackled some of these problems. And if the did tackle them, then how? My assumption is that, when you look at the banking sector, where they've done a lot in blockchain already… my assumption is that they haven't wedded themselves to just one vendor solution. I think we need to ask: what is it that we can borrow from other sectors, and what needs to be unique for [the energy industry]?

Also, in much the same way that POSC was created in response to a push from oil & gas operators rather than from the service companies that had developed their own proprietary data protocols, the Energistics team believed that "forces from on high" would probably be required to nudge the geoenergy industry towards a workable number of standards

5. Discussion and conclusions

5.1. Answers to the research questions

As noted in the beginning of this paper, the geoenergy industry will require an increasing degree of technological and commercial sophistication to continue to be a part of the world's sustainable energy mix. By putting forward case study evidence about how blockchain technologies have been applied throughout the marketplace, this paper makes a contribution to the state of the art in this area by exploring potential pathways for delivering value and improving the sustainability of the geoenergy sector with this innovation. To this end, Research Questions 1a and 1b asked how other industries are applying blockchain technologies in ways that might be different from what is happening in the geoenergy sector and, onward from this, what the geoenergy community can learn about the technology from these other industries. The case study offered several potentially helpful pieces of evidence on this front that we have coalesced into four themes.

The first of these themes is that blockchain has been very helpful in solving problems relating to digital assets, which explains why it was quickly adopted in parts of the market that are largely digital in nature, such as the finance sector. But the interviews revealed that, with a few notable exceptions, significantly less progress has been made in contexts that involve physical assets. Even less progress still has been achieved in situations involving continuously flowing physical assets (such as oil & gas) as opposed to physically distinct items (like, for example, diamonds or packages). There are almost certainly ways in which blockchain can and will eventually deliver value within the geoenergy domain, but it is likely that these instances will be focused on a few key areas of the sector rather than being a panacea for all of the industry's inefficiencies and challenges.

Second, the industries and consultants that have been bullishly selling blockchain solutions to the geoenergy sector are frequently less than familiar with the technical realities of the industry and, as a result, are probably over-estimating the value that these solutions can deliver. Blockchain is still a relatively nascent technology, and there is still a significant amount of experimentation happening in this area.

Third, at an abstract level, the technology successfully delivers value at points of custody transfer between organizations. Future attempts to apply blockchain in the geoenergy industry would therefore do well to focus on scenarios fitting that archetype.

Fourth, a recurring pattern that has emerged in earlier implementations of blockchain is that the people-related and organizational dimensions of the problem are usually underestimated. Companies typically do not want to sign on to blockchain projects that are already underway. Getting buy-in from these stakeholders and applying a more collaborative approach from the outset will improve the probability of success.

The case study interviews also brought into focus the importance of data standards and interoperability, which was a point that was also highlighted in the blockchain literature [36]. Research Question 2 was consequently added to determine how the geoenergy industry should approach this problem. The interviews revealed that, unlike the more internally directed approach that the industry used to address data standards in the past, any such moves in the blockchain domain should leverage existing standards as much as possible, thereby taking advantage of the blockchain-related learning that has happened in other sectors.

5.2. Implications for theory

This paper makes two theoretical contributions. First, it offers a potentially helpful reminder that some parts of the energy sector—-specifically, the upstream oil & gas industry—have already faced similar kinds of challenges and, in doing so, it shines light on earlier work in this area from many years ago [79,80] that should not be overlooked as the discussion continues to unfold in the literature. Second, this paper provides fresh case study evidence that directly responds to the call from Andoni et al. [36] to accelerate and improve the adoption of blockchain by promoting data standards that allow interoperability between different systems.

5.3. Implications for industry and policy

The evidence presented in this paper also carries with it important implications and practical tips for practitioners in the geoenergy sector and for policymakers who work in government departments connected to the industry. Several of the interviewees explained that the transparency that the creators of blockchain found so appealing actually has a few unhelpful consequences in a real-world business environment. The ability to see important aspects of every transaction that occurs within an industry would potentially cause a firm to unwittingly reveal its strategic intentions to competitors. An Intel manager summarized this dilemma succinctly by observing that "You can't have no secrets." It therefore follows that, for the geoenergy industry or almost any other market segment to expand the boundaries of what blockchain technology can do, it might be helpful if users were able to obfuscate or keep hidden some of the information within the distributed ledger. Until this problem is addressed, any potential benefits that blockchain might confer on its users could be eclipsed by the cost of revealing their strategic intentions.

One participant also pointed out that, in an industry that is as international as the geoenergy sector is [78], many of the blockchain solutions that the sector comes up with will quite likely cross international borders and criss-cross back and forth between legal jurisdictions. This presents a problem inasmuch as many countries and political blocs have strict laws governing the exportation of certain kinds of data. It is worth noting, however, that this is also a challenge that has faced prospective users of cloud computing resources [92]. In the short-term, the architects of blockchain solutions may have to be confined by these kinds of constraints; in the long-term, policymakers might need to consider revising their regulatory frameworks to keep pace with these technological developments and, in doing so, make possible the kinds of benefits and efficiencies that global blockchains can potentially deliver.

5.4. Recommendations for future research

The qualitative case study methodology used in this investigation may have been the "preferred strategy when 'how' or 'why' questions are being posed," but it is not without limitations. While every effort was made to arrive at objective truth by triangulating several different points of view, qualitative interviews are inherently limited in that they typically offer fewer "data points" than quantitative research. This paper put forward evidence from several people but, as diverse and outward-looking as those individuals may be, they all came from two organizations. Different perspectives and points of view may have been brought to the fore if our interviews had happened with people from a different part of the market. What is more, the use of quantitative methodological approaches—like, for example, a broader survey that involves more people than would be practical with interviews—would strengthen our confidence in the findings presented here. Future researchers in this area would be helpfully contributing to the literature by bringing to bear different methods to answer the questions asked here. Also, this paper essentially approached the topic of blockchain in the geoenergy sector from a conceptual point of view and asked fairly high-level questions about how these innovations have added value in other industries and how, by learning from other sectors, value could similarly be added in the geoenergy domain. But this contribution falls short of diving into the technical specifics of precisely how these results can be achieved. We accordingly hope that this paper will stimulate future investigations into system architectures and the technical details required to deliver these outcomes.

Acknowledgements

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Appendix A. Sample of representative questions used in semi-structured interviews

A.1 Questions intended to address Research Questions 1a and 1b

(i) Which industries are moving furthest and fastest with the application of blockchain?
(ii) How do you see blockchain delivering value in those industries?
(iii) How do you see blockchain impacting the competitive dynamics of these industries, and how have they impacted the relative profitability of the companies in that market space?
(iv) What are some industries getting wrong with blockchain?
(v) How has blockchain been applied in the geoenergy sector so far? Where has it already successfully delivered value, and where has it not?
(vi) How could the heightened degree of system-wide transparency that blockchain delivers cause problems for companies operating in the geoenergy market?

A.2 Questions intended to address Research Question 2

(vii) Please explain your perspective on the interoperability aspects of blockchain technology at the moment.
(viii) How are the technical specifics of blockchain different from the data exchange and interoperability problems that Energistics and its precursor organizations were trying to solve?
(ix) Based on how we've seen this challenge get managed with other kinds of technical standards in the geoenergy domain, how would you recommend we solve this in the context of blockchain?
(x) Would it make sense to try and standardize data standards within the geoenergy industry, or should some of this standardization happen via the larger market?

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